

## Arrays in Space to detect Upward $\tau$ and Highest Altitude Showers

**D.Fargion**

Physics Department and INFN Rome University 1, Pl.A.Moro 2, 00185, Rome, Italy

**Abstract.** Ultra High Energy, UHE, upward Tau neutrinos  $\nu_\tau, \bar{\nu}_\tau$ , above hundred TeVs and up to tens PeV energies, of relevant astrophysical nature, may lead to *UHE* Taus and consequent Up-ward Tau air-Showers (**UPTAUS**) after interaction on Earth crust surface. The UPTAUS discovery may open a new UHE Tau Neutrino Astrophysics. A new generation of Gamma, X, optical and Radio Arrays in Space may discover, in the same Auger spirit, such up-coming Air-showers as well as an additional Tau signal: the nearly Horizontal Tau AIR-Shower (**HORTAUS**) originated by *UHE* neutrinos  $\tau$  at  $10^{19} \text{ eV}$  energies arising from a thin Earth crust corona at few tens of degree below the horizons; a degree above the horizons, there should be over common diffused cosmic ray albedo, an additional High Altitudes (nearly Horizontal) Showers (**HIAS**), by more common Cosmic Rays primaries at PeVs up to EeV and ZeV energies, both of hadronic or of electro-magnetic  $\gamma$  nature. Mini-arrays detectors in high Altitude Balloons tails facing the horizons and the Earth below may also reveal both UPTAUS, and HIAS, and more rarely HORTAUS. Gamma Burst, Cherenkov flashes and rarer muons observed by high mountains peak arrays or high quota balloon array may better probe UPTAUS and HORTAUS. Present and future X-Gamma satellites as Beppo-Sax may be also able to discover HORTAUS and HIAS discovering transient events by UHE source (as the Crab) while in occultation by Earth. Because of the large shower distances and the Earth magnetic field, HIAS and HORTAUS showers will be split in a Twin-Beams fan-shaped wide arc, orthogonal to  $B_\oplus$ , with a strong azimuths modulation. Gamma bursts and rare muons or neutrons at the horizon, associated with HIAS, HORTAUS may be discovered by Glast and AMS satellite.

positions as well as to highest energy particle physics. Cosmic Rays studies clarified fundamental physics as the matter and anti-matter (electron-positron) or the pion-muon interaction nature opening the gate toward present quark and lepton understanding of elementary particles. Air Showers are commonly downward chain reactions originated by incoming cosmic rays (nucleons, nuclei, gamma) on upper Earth Atmosphere. Earth itself absorbs most upcoming cosmic rays, suppressing also PeVs upward muons secondaries produced by noisy Atmospheric  $\nu_\mu, \bar{\nu}_\mu$  Neutrinos. Downward Air-Showers, hadronic or electro-magnetic, have been widely modeled and measured. At first sight Up-ward Air-showers are totally forbidden by the severe opacity of the Earth below both to muons as well as (by terrestrial growing shadowing) also to *UHE* neutrinos,  $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$  at tens TeVs energies and above. The surviving upward *GeV*s – *TeV*s muons, founded in AMANDA, Baikal, MACRO detectors are *not* usually, able to lead to any upward Air showers. Moreover *UHE*  $\nu_e, \bar{\nu}_e$  will produce very confined shower (the LPM, Landau, Pomeranchuk, Migdal effect) within a very thin earth layer (less than few meters) immediately buried in there; upward *UHE*  $10^{13} \div 10^{14} \text{ eV}$ , atmospheric or astrophysical  $\nu_\mu, \bar{\nu}_\mu$  and their muons produced on a thin earth crust (few Kms depth) will freely escape from the Earth with very rare catastrophic bremsstrahlung showering in the atmosphere. *UHE*  $\nu_\tau, \bar{\nu}_\tau$  have been usually neglected due to the Tau short lifetime. Moreover one should remind that *UHE*  $\nu_\tau, \bar{\nu}_\tau$  are rarely ( $< 10^{-5}$ ) produced in high energy astrophysical sources. However the recent discovery by Super Kamiokande of a full flavor mixing  $\nu_\mu \nu_\tau$  implies a nearly homogeneous abundance of all *UHE*  $\nu_e, \nu_\mu, \nu_\tau$  flavors (Fargion 1997, 1999).

### 1 Introduction: Downward Air-Showers

Downward Air-Showers have been studied in last century leading to new advances in cosmic rays spectra and com-

Correspondence to: daniele.fargion@roma1.infn.it

### 2 UPTAUS: The Upward Tau Air-shower

The Upward *UHE*  $\nu_\tau$ , being less opaque to the Earth, it may interact within the terrestrial surface crust (nearly Kms depth) leading to  $10^{14} \div 10^{16} \text{ eV}$ s events in Tau Air-Shower UPTAUS form (Fargion 2000). Correlation between UPTAUS

and observed Terrestrial Gamma Flashes (TGF) has been noted (Fargion 2000,2001, HE2.5). Here we present and discriminate the three main new kind of Air-Showers to be detectable on balloons or satellites.. (1) Upward  $\tau$  Air-Shower UPTAUS around PeVs energies. (2) The nearly horizontal HORTAUS within  $10^{17} - 10^{19} \text{ eV}$  energies upcoming from the horizons edges.(3) A high altitude Air-Showers originated by UHECR at the edges of GZK energies, HIAS. The nature of UPTAUS and HORTAUS are analogous, but at different energy windows:  $10^{15} - 10^{15.5} \text{ eV}$ ,  $10^{19} \text{ eV}$  respectively. Their bang in matter and bang in air remind the *Tau Double Bang* (Learned,Pakvasa 1995). They are different respect downward air-showers. Indeed the  $\tau$  decay is bounded to a limited size and has an hybrid electro-magnetic and hadronic interaction with matter. The  $\tau$  main air-shower channels must reflect the rich and structured behaviours of  $\tau$  decay modes. Let us label the main UHE decay channels (hadronic or electro-magnetic) and the consequent air-shower imprint, with corresponding probability ratio in following Table. The UPTAU

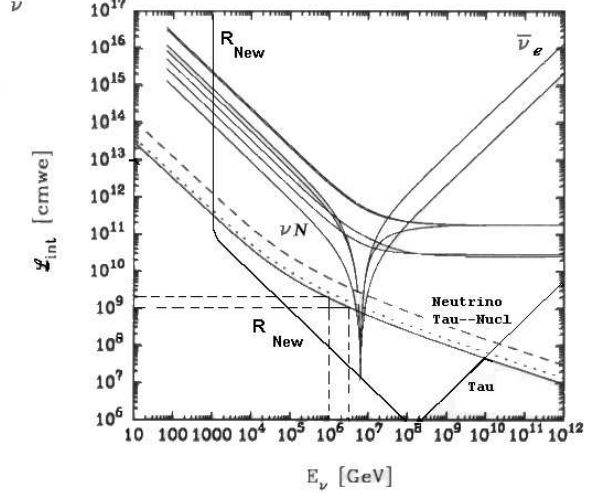
TABLE 1  
TAU AIR SHOWER CHANNELS

Decay	Secondaries	Probability	Air-shower
$\tau \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$	$\mu^-$	$\sim 17.4\%$	Unobservable
$\tau \rightarrow e^- \bar{\nu}_e \nu_\tau$	$e^-$	$\sim 17.8\%$	1 Electromagnetic
$\tau \rightarrow \pi^- \bar{\nu}_\pi \nu_\tau$	$\pi^-$	$\sim 11.8\%$	1 Hadronic
$\tau \rightarrow \pi^- \pi^0 \nu_\tau$	$\pi^-, \pi^0 \rightarrow 2\gamma$	$\sim 25.8\%$	1 Hadronic, 2 Electromagnetic
$\tau \rightarrow \pi^- 2\pi^0 \nu_\tau$	$\pi^-, 2\pi^0 \rightarrow 4\gamma$	$\sim 10.79\%$	1 Hadronic, 4 Electromagnetic
$\tau \rightarrow \pi^- 3\pi^0 \nu_\tau$	$\pi^-, 3\pi^0 \rightarrow 6\gamma$	$\sim 1.23\%$	1 Hadronic, 6 Electromagnetic
$\tau \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$	$2\pi^-, \pi^+$	$\sim 10\%$	3 Hadronic
$\tau \rightarrow \pi^- \pi^+ \pi^0 \nu_\tau$	$2\pi^-, \pi^+, \pi^0 \rightarrow 2\gamma$	$\sim 5.18\%$	3 Hadronic, 2 Electromagnetic

**Fig. 1.** The Table above shows the characteristic Tau Air-Shower originated by an Ultra High Energy neutrino. The decay channels are ruled by elementary particle Physics, leading to different Shower composition: Hadronic, Electro-Magnetic or an hybrid one. These signatures should be verified by a large set of UPTAUS and HORTAUS. The high atmosphere density on Sea level makes UPTAUS poor source of UHE surviving muon secondaries; also HORTAUS originated from a mountain chain are muon-poor. On the contrary HORTAUS and HIAS originated at high quota may be muon rich

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cascade occur at high quota where atmosphere is less dense and imply longer final shower tails. For this reasons the scale time of the  $\gamma$  are longer (hundreds microseconds) and harder than downward ones. The UPTAUS maybe therefore bent in a thin-twin fan arcs few degree size by Earth magnetic field leading to a twin shower beams in deflected (positive-negative) thin elliptical cones. The deflection has a strong azimuth and zenith imprint as well as a characteristic geological signature (by Earth density). It is negligible observing to North and South, while it is maximal observing East and West. Deflection and opening angles are maximal in Asia where terrestrial magnetism is largest as indeed observed in TGFs data (Fargion 2000). If the Twin-Beam UPTAUS is observed by a wide spaced array in Space its spatial and temporal (Fargion 2000,2001) arrival structure should be observed. The  $\nu_\tau$ ,  $\bar{\nu}_\tau$ - $\tau$  HORTAUS, may be generated efficiently also in front of a mountain chains : their detection on ground or



**Fig. 2.** The UHE neutrino ranges  $\nu_\tau N$  as a function of UHE neutrino energy in Earth with overlapping the resonant  $\bar{\nu}_e e$ , interactions (Gandhi et al 1998) and  $\tau$  ranges (Fargion ICRC 1999,2001).  $R_{New}$  shows the interaction length due to New physics for rock  $\rho = 3$

from the mountain arrays has been discussed (Fargion et al ICRC 26,1999; Fargion ICRC 27,HE 2001). The expression that describe the probability to observe a UPTAUS and HORTAUS Shower by an UHE  $\nu_\tau$ ,  $\bar{\nu}_\tau$  is suppressed by Earth opacity and it is proportional to the probability to make a  $\tau$  within the Earth (or mountain) crust:

$$P(\theta, E_\nu) = e^{-\frac{2R_\oplus \sin \theta}{R_{\nu\tau}(E_\nu)}} (1 - e^{-\frac{R_\tau(E_\tau)}{R_{\nu\tau}(E_\nu)}}). \quad (1)$$

Here  $\theta$  is the angle below the horizons while standing on the Earth (see Fargion 2001). From height  $h_2$  (for instance the satellite orbit), the same expression becomes:  $P(\theta, E_\nu) =$

$$e^{-\frac{2\sqrt{(R_\oplus + h_2)^2 \sin^2 \theta - [(R_\oplus + h_2)^2 - R_\oplus^2]}}{R_{\nu\tau}(E_\nu)}} (1 - e^{-\frac{R_\tau(E_\tau)}{R_{\nu\tau}(E_\nu)}}). \quad (2)$$

where  $\theta$  from height  $h_2$  reaches a minimal values when it is just tangent to the Earth: then  $\theta_{2min}$  is:

$$\theta_{2min} = \frac{\sqrt{(R_\oplus + h_2)^2 - R_\oplus^2}}{(R_\oplus)} \quad (3)$$

This angle from satellites at height  $h_2 = 500 \text{ Km}$  is 22.4 degrees below the horizons. The visible Earth surface from a satellite, like BATSE, at height  $h \sim 400 \text{ Km}$  and the consequent effective volume for UHE  $\nu_\tau N$  PeVs interaction and  $\tau$  air shower beamed within  $\Delta\Omega \sim 2 \cdot 10^{-5} \text{ rad}^2$  is: (note  $\langle \rho \rangle \simeq 1.6$  because 70 % of the Earth is covered by seas) The effective volume and the event rate should be reduced, at large nadir angle ( $\theta > 60^\circ$ ) by the atmosphere depth and opacity (for a given  $E_\tau$  energy). Therefore the observable volume may be reduced approximately to within  $15 \text{ Km}^3$  values and the expected UHE PeV event rate is (Fargion 2000)

$$N_{ev} \sim 150 \left( \frac{h}{400} \right) \frac{\text{events}}{\text{year}} \quad (E_\tau \sim 3 \text{ PeV}) \quad (4)$$

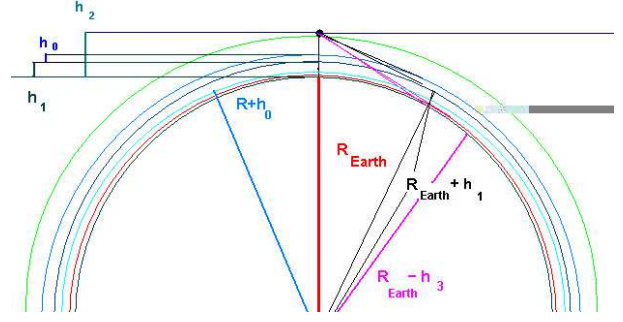


**Fig. 3.** The Upward Tau Air-Shower *UPTAUS* originated by UHE  $\nu_\tau$  (white track) crossing the Earth and interacting within the thin Earth Crust layer. The UHE  $\tau$  track (red line) at PeVs decay in air leading to a complex shower: a twin-split green and violet short spirals stand respectively for positron and electron fan-shaped components; longer twin-split blue-orange tracks describe the positive-negative muons. Final surviving Bremsstrahlung gamma, X and Cherenkov photons are flashing in a twin wide, but thin, yellow fan-shaped beams to satellite.

It is well possible that UPTAUS have been already observed (Fargion 2000,2001) as upward Terrestrial Gamma Flashes. Present and future satellite as Glast should be able to confirm the UPTAUS discover.

### 3 HIAS :The High Altitude air-Shower

Earth atmosphere is continuously reflecting a noisy cosmic ray albedo due mainly to neutral pion decays in gamma upward; these pions are secondaries of common incoming cosmic rays hitting the Earth atmosphere. Their low energy statistical overlapping is not source of any sudden showers. However the detection of UPTAUS and in particular of HORTAUS from satellite is disturbed by a different upcoming competitive shower signal: the HIAS, the High Altitude, nearly tangential, UHE cosmic ray, Showers. Indeed the atmosphere depth at slant depth greater than  $210^3 \text{ gcm}^{-2}$  is commonly opaque (suppression  $10^{-3}$ ) to most cosmic rays showers (but not to muons ones). Then UHECR cannot send signals upward while crossing all the Earth dense atmosphere. On the contrary at very high altitude air become so diluted that it may become again transparent to horizontal UHECR. At more high quota the paucity of air makes rare the UHECR interactions and there are not showers again. There is an optimal height which permits to tangential UHECR to lead to powerful showers. The determination of this height is not obvious. The author is not aware of any derivation of this height value. Here we derive a new general expression. The geometry of the problem needs a simple diagram. The properties of HORTAUS are comparable to UPTAUS but they are bounded in a thin terrestrial layer and at a higher (EeV) energy band. The height  $h_0$  is the characteristic exponential air density height,  $h_1$  is the last transparent air quota where High Altitude Air-Shower take place,  $h_2$  is the satellite or balloon quota,  $h_3$  is the deepest distance from the Earth surface for Horizontal HORTAUS. We first estimate the atmo-



**Fig. 4.** The figure above shows the trajectories for nearly Horizontal Tau Air-Shower HORTAUS, by an UHR  $\tau$  made by UHE  $\nu_\tau$  at  $10^{19}$  eV energies (white track) crossing the Earth crust at depth  $h_3$  (few Km) and interacting with tens or a hundred terrestrial Km layers. The same upcoming HORTAUS hits the observer (mountains, balloons, satellite) at height  $h_2$ . HIAS produce at a characteristic quota  $h_1$  a long track shower within a thin corona height  $h_0$ , (defined by density decay law), reaching the observer (balloons, satellite) at quota  $h_2$ .

sphere depth crossed horizontally:

$$X = \int_{-\infty}^{+\infty} \sqrt{(R_\oplus + h_2)^2 - (R_\oplus + h_1)^2} n_0 e^{-h/h_0} dx \quad (5)$$

We then infer that this slant depth is comparable to common vertical one. This request defines and fix the fine tuned height  $h_1$  value. Because for satellites the distances are large we may approximate above integral in:

$$X = \int_{-\infty}^{+\infty} n_0 e^{-h/h_0} dx \equiv n_0 h_0 \quad (6)$$

$$\frac{X}{n_0} \simeq 2 \int_0^{+\infty} e^{-h_1/h_0} e^{-\frac{x^2}{2(R_\oplus + h_1)h_0}} dx \cong h_0 \quad (7)$$

The consequent transcendental equation that fix the height  $h_1$  is

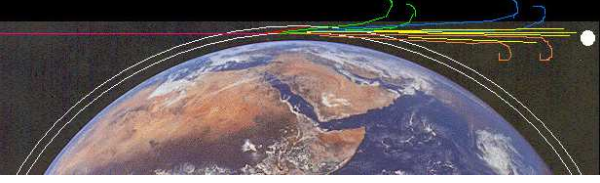
$$2\sqrt{\pi} e^{-h_1/h_0} \sqrt{(R_\oplus + h_1)h_0} = h_0 \quad (8)$$

$$\frac{h_1}{h_0} = \frac{3}{2} \ln 2 + \frac{1}{2} \ln \left( \frac{R_\oplus + h_1}{h_0} \right) - \ln A + \frac{1}{2} \ln \pi \quad (9)$$

Where  $h_0 = 8,55$  Km,  $R_\oplus$  is the Earth radius, A is an additional parameter of order of unity that calibrate the shower slant depth to its incoming energy as well as to its hadronic or electro-magnetic interaction nature. After simple substitution and applying known empirical laws for the logarithmic growth of the X slant depth one derives respectively for hadronic and gamma UHECR showers:

$$A_{Had.} = 0.792 \left[ 1 + 0.02523 \ln \left( \frac{E}{10^{19} \text{ eV}} \right) \right] \quad (10)$$

$$A_\gamma = \left[ 1 + 0.04343 \ln \left( \frac{E}{10^{19} \text{ eV}} \right) \right] \quad (11)$$



**Fig. 5.** The nearly horizontal High Altitude Showers, *HIAS*. Their Hadronic or electro-magnetic interaction defines the altitudes where the shower is originated and propagate. The terrestrial magnetic field leads to electron pairs and muon pairs splitting and a very wide twin gamma beam in a fan shape, upward and downward.

The corresponding solution for the transcendental equations above are:

$$h_{1_{Had.}} = 44.08 - 8.55 \ln[1 + 0.02523 \ln\left(\frac{E}{10^{19} \text{eV}}\right)] \text{ Km} \quad (12)$$

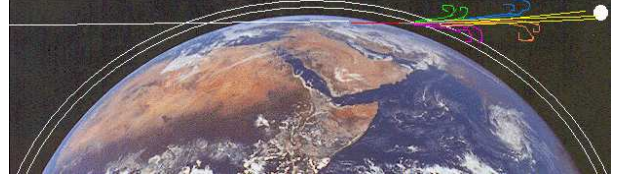
$$h_{1_{\gamma}} = 42.09 - 8.55 \ln[1 + 0.04343 \ln\left(\frac{E}{10^{19} \text{eV}}\right)] \text{ Km} \quad (13)$$

The characteristic distances crossed from this altitudes to the satellites are hundred of Kilometers. Therefore there is an important role of the magnetic fields in bending the *HIAS* trajectories in a fan-shaped arc. This allow to observe a *HIAS* not only at its origination direction (nearly one degree above the Earth edge, from a satellite) but also below the Earth horizons. Obviously the down-ward component of the *HIAS* may reach back the Earth but with a negligible strength. Therefore, for the same reason, there are not *HIAS* appearing above (one degree) from the Earth horizons observing on satellites. On the contrary *HIAS* may hit high quota balloons (20 – 30 *Kms*) quota both mainly above the terrestrial horizons and rarely nearly horizontally and more rarely below the horizons. Therefore balloons (possibly in arrays) are ideal detectors for *HIAS*. The upcoming *HIAS* are also important because they may be confused as a *HORTAUS* from satellites, but not in mountain observatories. The trajectory and the morphology of the two events maybe discriminate. *HIAS* while being able to appear below the horizons from satellite, cannot completely mimic *UPTAUS* because their track, spectra, timing are quite different.

#### 4 HORTAUS :The Horizontal Tau Air-shower

The possibility to UHECR neutrino to slip tangent to Earth crust at optimal neutrino interaction length and longest Tau range makes them ideal signals as *HORTAUS*. Their maximal probability occurs as shown in Fig2, at the crossing of Tau-Neutrino Lengths near  $E_{\nu_{\tau}} = 10^{19} \text{eV}$ , near GZK cut off bounds(Fargion,Mele,Salis 1999) where neutrino interaction lengths is comparable to the Tau one. At the same energy range one may find the characteristic height, or negative depth,  $h_3$  few Km, where the *HORTAUS* should begin to make a UHE Tau; consequently Tau shower should deploy neither at too low atmosphere (being absorbed), nor at

too high atmosphere (where no shower may be amplified). *HORTAUS* may also turn upward by geo-magnetic fields. In particular from a mountain *HORTAUS* within  $10^{16-19} \text{eV}$  may appear at angles below the original ones leading to more frequent (apparent) *UPTAUS* events; their timing and spectra and morphology is different from direct PeVs *UPTAUS*. The height where Tau decay which define also the optimal Tau energy equation for *HORTAUS* is analogous, but more complex than the *HIAS* one. The transcendental equation that



**Fig. 6.** The Horizontal Tau Air-Shower *HORTAUS* originated by an Ultra High Energy neutrino at  $10^{19} \text{eV}$  energies (white track) crossing the Earth and interacting within Earth Crust layer. The UHE Tau track (red line) decay in air leading to a longer complex shower comparable to the described ones above

defines the Tau distance  $c\tau$  analogous to the *HIAS* one are:

$$\int_0^{+\infty} n_0 e^{-\frac{\sqrt{(c\tau+x)^2 + R_{\oplus}^2} - R_{\oplus}}{h_0}} dx \cong n_0 h_0 A \quad (14)$$

$$\int_0^{+\infty} n_0 e^{-\frac{(c\tau+x)^2}{2h_0 R_{\oplus}}} dx \cong n_0 h_0 A \quad (15)$$

$$c\tau = \sqrt{2R_{\oplus} h_0} \sqrt{\ln\left(\frac{R_{\oplus}}{c\tau}\right) - \ln A} \quad (16)$$

Where  $A = A_{Had.}$  or  $A = A_{\gamma}$  are the same defined in eq.10 – 11. The solution of this equation leads to a characteristic UHE  $c\tau_{\tau} = 546 \text{ Km}$  decay distance at height  $h = 23 \text{ Km}$  where the *HORTAUS* begins to shower. This imply a possibility to discover efficiently by satellite and balloons arrays UHE  $\nu_{\tau}$ ,  $\bar{\nu}_{\tau}$  up to  $1.11 \cdot 10^{19} \text{eV}$ . Other consequences of the *HORTAUS*, *UPTAUS* and *HIAS* physics will be shown soon elsewhere. Arrays in valleys, mountains, airlines, balloons and satellites should easily discover their traces.

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